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<b>14. ABSTRACT</b>  Recent advances in quantum optics resulting from the study of atomic coherence effects have lead to substantial breakthroughs in quantum computing, metrology, high precision spectroscopy, telecommunications, generation of high- and low-frequency coherent radiation, etc. Using the most recent theoretical and experimental tools, we work on both the theory of basic physical phenomena and on practical implementation of these theoretical ideas.					
<b>15. SUBJECT TERMS</b> Ultraslow Light; stopping light; squeezed light, anomolous stimulated Brillouin scattering; stored light; nonlinear magneto-optics; atomic coherence; optically dense media; optical magnetometry; quantum coherence; free-electron lasers; lasing without inversion; LWI; canonical statistics; Bose-Einstein condensates; canonical statistics.					
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REPORT**

**for**

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**FUNDAMENTAL AND APPLIED QUANTUM OPTICS**

**Principal Investigator: Marlan O. Scully**

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**15 January 2003**

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## Contract Information

Contract Number	N00014-99-1-0001
Title of Research	Fundamental and Applied Quantum Optics
Principal Investigator	Marlan O. Scully
Organization	Texas A&M University

## Technical Section

This section will describe the objectives of the contract.

### Ultralow light and applications

- Stopping light via hot atoms
- Using slow light to enhance acousto-optical effects: Application to squeezed light
- Anomalous stimulated Brillouin scattering via ultralow light
- Transporting, multiplexing, and time reversing stored light.

### Nonlinear magneto-optics

- Enhancement of magneto-optic effects via large atomic coherence in optically dense media
- Large polarization rotation in dense Rb vapor
- Quantum limit of optical magnetometry in the presence of ac-Stark shifts
- Ac-Stark shifts in the nonlinear Faraday effect
- Compensation of ac-Stark shifts in optical magnetometry

### Laser physics, new sources of radiation and devices for its detection

- Infrared generation in low-dimensional semiconductor heterostructures via quantum coherence
- Efficient infrared imaging upconversion via quantum coherence
- Maser action in a bimodal cavity

### Free-Electron Lasers without inversion

- Free-electron laser without inversion: Gain optimization and implementation scheme
- Broadband optical gain via interference in the free electron laser: principles and proposed realizations

## **Fundamental Physics**

- Canonical statistics of ideal Bose-Einstein condensates
- Equivalence of the Master Equation Approach to the Canonical ensemble approach for an Ideal Bose Gas
- Inhibition of Decoherence due to Decay in a Continuum
- Accelerating decay by multiple 2- $\pi$  pulses
- Asymmetries between absorption and stimulated emission in driven three-level systems
- Mixed electromagnetically and self-induced transparency
- On mechanisms that enforce complementarity.

## **Technical Approach**

This section will describe the Technical Approach taken by the contractor.

Recent advances in quantum optics resulting from the study of atomic coherence effects have lead to substantial breakthroughs in quantum computing, metrology, high precision spectroscopy, telecommunications, generation of high- and low-frequency coherent radiation, etc. Using the most recent theoretical and experimental tools, we work on both the theory of basic physical phenomena and on practical implementation of these theoretical ideas.

## **Accomplishments**

This section will describe the accomplishments for Fiscal Year 2001 for the contract

## **Ultralow light and applications**

- Stopping light via hot atoms

We prove that it is possible to freeze a light pulse (i.e., to bring it to a full stop) or even to make its group velocity negative in a coherently driven Doppler broadened atomic medium via electromagnetically induced transparency (EIT). This remarkable phenomenon of the ultraslow EIT polariton is based on the spatial dispersion of the refraction index  $n(\omega, k)$ , i.e., its wave number dependence, which is due to atomic motion and provides a negative contribution to the group velocity. This is related to, but qualitatively different from, the recently observed light slowing caused by large temporal (frequency) dispersion.

- Using slow light to enhance acousto-optical effects: Application to squeezed light

We propose a technique for achieving phase matching in Brillouin scattering in a dielectric fiber doped by three-level Lambda-type ions. This can lead to a dramatic increase of efficiency of ponderomotive nonlinear interaction between the electromagnetic waves and holds promise for applications in quantum optics such as squeezing and quantum nondemolition measurements.

- Anomalous stimulated Brillouin scattering via ultraslow light

We study stimulated Brillouin scattering (SBS) in an ultradispersive coherent medium, and show that the properties of SBS change drastically when the group velocity of light in the material approaches or becomes less than the speed of sound. In particular, forward SBS not allowed in a dispersionless bulk medium takes place in the coherent medium.

- Transporting, multiplexing, and time reversing stored light.

We studied the basic issues central to the storage of quantum information in a coherently prepared atomic medium such as the role of adiabaticity. We also proposed and demonstrated transporting, multiplexing, and time reversing stored light.

## **Nonlinear magneto-optics**

- Enhancement of magneto-optic effects via large atomic coherence in optically dense media

We utilize the generation of large atomic coherence in optically dense media to enhance the resonant nonlinear magneto-optic effect by several orders of magnitude, thereby eliminating power broadening and improving the fundamental signal-to-noise ratio. A proof-of-principle experiment is carried out in a dense vapor of Rb atoms. Applications such as optical magnetometry, the search for Violations of parity and time-reversal symmetry, and nonlinear optics at low light levels are feasible.

- Large polarization rotation in dense Rb vapor

We report dramatic enhancement of the non-linear Faraday rotation in optically thick Rb vapor. Polarization rotation angles as large as 10 radians were observed for the first time for sub-Gauss magnetic fields. We show that the effect of radiation trapping leads to the saturation and subsequent degradation of rotation with the increasing of atomic density.

- Quantum limit of optical magnetometry in the presence of ac-Stark shifts

We analyze systematic (classical) and fundamental (quantum) limitations of the sensitivity of optical magnetometers resulting from ac Stark shifts. We show that in contrast to absorption-based techniques, the signal reduction associated with classical broadening can be compensated in magnetometers based on phase measurements using electromagnetically induced transparency (EIT). However due to ac Stark-associated quantum noise the signal-to-noise ratio of EIT-based magnetometers attains a maximum value at a certain laser intensity. This value is independent on the quantum statistics of the light and defines a standard quantum limit of sensitivity. We demonstrate that an EIT-based optical magnetometer in Faraday configuration is the best candidate to achieve the highest sensitivity of magnetic-field detection and give a detailed analysis of such a device.

- Ac-Stark shifts in the nonlinear Faraday effect

The frequency of the dark resonance in coherent population trapping experiments has been measured as a function of the degree of ellipticity and the intensity of the probe Light. The results have been used to find the quantum limit of sensitivity of an optical magnetometer based on the nonlinear Faraday effect.

- Compensation of ac-Stark shifts in optical magnetometry

The ac Stark shift of the resonance frequency of the nonlinear magneto-optic effect (NMOE) results in a fundamental broadening of this resonance which limits the precision of optical magnetometry based on NMOE. We have studied the dependence of the ac Stark shift versus frequency of the probing laser for the D1 and D2 lines of  $^{87}\text{Rb}$ , and have shown that there exists a frequency where the shifts from different hyperfine components of the upper level cancel each other. This holds promise for an in-principle increase in the sensitivity of optical magnetometers. The influence of buffer gas on Faraday rotation and ac Stark shifts is also considered.

## **Laser physics, new sources of radiation and devices for its detection**

- Infrared generation in low-dimensional semiconductor heterostructures via quantum coherence

A scheme for infrared generation without population inversion between subbands in quantum-well and quantum-dot lasers is presented. The scheme is based on the resonant nonlinear mixing of the optical laser fields on the two interband transitions that are generated in the same active region and that serve as the coherent drive for the infrared field. This mechanism for frequency down-conversion does not rely upon any ad hoc assumptions of long-lived coherences in the semiconductor active medium, and it should work efficiently at room temperature with injection current pumping. For optimized waveguide and cavity parameters, the intrinsic efficiency of the down-conversion process can reach the limiting quantum value corresponding to one infrared photon per one optical photon. Due to the parametric nature of infrared generation, the proposed inversionless scheme is especially promising for long-wavelength (far-infrared) operation.

- Efficient infrared imaging upconversion via quantum coherence

We show that quantum coherence can be used to achieve marked improvement in the efficiency of the process of infrared upconversion. In one particular example which we analyze in detail, we show that it is possible to convert infrared radiation at a wavelength of 100  $\mu\text{m}$  to the visible with essentially 100% efficiency while maintaining diffraction-limited imaging of the infrared field.

- Maser action in a bimodal cavity

The work of Meyer, Scully, and Walther [Phys. Rev. A 56, 4142 (1997)] is generalized to study the operation of a two-mode maser with particular reference to the question of mode-mode correlations. The explicit expression for the detailed balance steady-state photon distribution has been derived. It is shown that the two-mode maser exhibits much stronger sub-Poissonian statistics for each mode. The photon-number distributions are found to be quite sensitive to the presence of blackbody photons in the cavity. The interferences among contributions from different dressed states enable one to obtain the phase of the transmission amplitude of finding the atom in the initial excited state by considering a set of two measurements involving two different initial states of the atom-field system.

## **Free-Electron Lasers without inversion**

- Free-electron laser without inversion: Gain optimization and implementation scheme

We consider a scheme of two noncollinear wigglers with an intermediate magnetic drift region, constituting a free-electron laser without inversion (FELWI). Two mechanisms of phase shifts in the drift region between the wigglers owing to a series of magnetic lenses can give rise to FELWI: velocity- and angle-dependent shifts. An appropriate combination of these shifts is shown to provide the conditions for amplification without inversion. The phase shifts optimizing the gain are found. A specific scheme for the drift region is suggested.

- Broadband optical gain via interference in the free electron laser: principles and proposed realizations

We propose experimentally simplified schemes of an optically dispersive interface region between two coupled free electron lasers (FELs), aimed at achieving a much broader gain bandwidth than in a conventional FEL or a conventional optical klystron composed of two separated FELs. The proposed schemes can universally enhance the gain of FELs, regardless of their design when operated in the short pulsed regime.

## **Fundamental Physics**

- Canonical statistics of ideal Bose--Einstein condensates

Within the canonical ensemble, a partially condensed ideal Bose gas with arbitrary single particle energies is equivalent to a system of uncoupled harmonic oscillators. We exploit this equivalence for deriving a formula which expresses all cumulants of the canonical distribution governing the number of condensate particles in terms of the poles of a generalized Zeta function provided by the single-particle spectrum. This formula lends itself to systematic asymptotic expansions which capture the non-Gaussian character of the condensate fluctuations with utmost precision even for relatively small, finite systems, as confirmed by comparison with exact numerical calculations.

We use these results for assessing the accuracy of a recently developed master equation approach to the canonical condensate statistics; this approach turns out to be quite accurate even when the master equation is solved within a simple quasi-thermal approximation. As a further application of the cumulant formula we show that, and explain why, all cumulants of a homogeneous Bose-Einstein condensate “in a box” higher than the first retain a dependence on the boundary conditions in the thermodynamic limit.

- Equivalence of the Master Equation approach to the canonical ensemble approach for an ideal Bose gas

A picture of the condensate statistics of a confined Bose gas, which is more relevant to recent experimental realizations, can be obtained by the canonical ensemble approach. Nevertheless, handling the particle number conservation condition entering therein is a formidable task. A recent method developed to deal with this problem is a non-equilibrium master equation approach based on the quantum theory of laser. We show how the equilibrium solution of this master equation is faithful to the canonical ensemble.

- Inhibition of Decoherence due to Decay in a Continuum

We propose a scheme for slowing down decay into a continuum. We make use of a sequence of ultrashort 2 pulses applied on an auxiliary transition of the system so that there is a destructive interference between the two transition amplitudes one before the application of the pulse and the other after the application of the pulse. We give explicit results for a structured continuum. Our scheme can also inhibit unwanted transitions

- Accelerating decay by multiple 2- $\pi$  pulses

We show how a control of the dynamics of a decay process can be achieved by the application of a series of 2 pulses on an auxiliary transition. The 2 pulse changes the phase of the ground state by while leaving the phase of the excited state unaltered. This produces quantum interferences between the transition amplitudes for evolution in the short interval, just before and after the 2 pulse. Such an interference under suitable tailoring of the density-of-states of the bath and the time leads to accelerated decay.

- Asymmetries between absorption and stimulated emission in driven three-level systems

We present a physical picture explaining the asymmetries between absorption and stimulated emission occurring in the driven three-level systems. Based on a dressed-state picture, we obtain transition rates for absorption and stimulated emission separately, and show that the cancellation of absorption in the Lambda- and V-type systems are originated from different physical mechanisms. Furthermore, a simple analogy can be applied to cascade-type systems to show the absorption enhancement at two-photon resonance.



- Mixed electromagnetically and self-induced transparency

We show that application of self-induced transparency (SIT) solitons as a driving field in V-type electromagnetically induced transparency (EIT) leads to "mixed induced transparency" (MIT) that nicely combines the best features of both SIT and EIT.

- On mechanisms that enforce complementarity

In a recent publication Luis and Sanchez-Soto arrive at the conclusion that complementarity is universally enforced by random classical phase kicks. We disagree. One could just as well argue that quantum entanglement is the universal mechanism. Both claims of universality are unjustified, however.

## **Publications/Patents/Presentations/Honors Report**

### ***Publications***

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### **Books or chapters**

1. AB Matsko, O Kocharovskaya, Y Rostovtsev, GR Welch, AS Zibrov, MO Scully, "Slow, ultraslow, stored, and frozen light," *Advances In Atomic Molecular And Optical Physics*, **46**: 191-242 (2001).
2. M. O. Scully, H. Carmichael, and R. Glauber (Editors), *Directions in Quantum Optics: A Collection of Papers Dedicated to the Memory of Dan Walls, Including Papers Presented at the Tamu-Onr Workshop Held at Jackson, Wyoming, U. S. A., 26-30 July 1999* (Springer, Berlin, 2001).
3. J. A. Bergou, B.-G. Englert, M. Lax, M. O. Scully, H. Walther, and M. S. Zubairy, "Quantum theory of the laser," *Handbook of Optics* Vol. **IV**, Ch. 26 (McGraw Hill, New York 2000).

### **Patents filed**

*Detecting Infrared Radiation*, application made through Texas A&M University, file no. TAMUS 1750.

### **Invited presentations**

1. "Ultraslow and Frozen Light Applied to Quantum Computing and Quantum Noise Suppression," Society of America Annual Conference, Orlando, FL, October 2002
2. "Stopping light with hot atoms and time reversing light," Institute for Theoretical Physics Conference, Santa Barabara, CA, July 2002
3. "Frozen Light: the Tip of the Iceberg," Eastman Lecture (Optical Society of America), University of Maryland, April 16, 2002

4. A. S. Zibrov, L. Hollberg, V. L. Velichansky, M. O. Scully, M. D. Lukin, H. G. Robinson, A. B. Matsko, A. V. Taichenachev, and V. I. Yudin, "Destruction of darkness: optical coherence and multi-wave mixing in rubidium vapor," *Quantum Optics*, July 2000, Novosibirsk, Russia. Published: CP551, *Atomic Physics 17*, edited by E. Arimondo, P. DeNatale, and M. Inguscio, American Institute of Physics, p. 204, 2001.
5. M. O. Scully, "Improving the Efficiency of an Ideal Heat Engine: The Quantum Afterburner," 31<sup>st</sup> Winter Colloquium on the Physics of Quantum Electronics, January 2001, Snowbird, UT.
6. G. Welch and M. O. Scully, "Optical Magnetometry in Dense Coherent Media," 31<sup>st</sup> Winter Colloquium on the Physics of Quantum Electronics, January 2001, Snowbird, UT.
7. M. O. Scully, "Quantum Search implementation via atomic coherence," ONR Workshop on Quantum Optics, Jackson Hole, WY, August, 2000.
8. G. Welch and M. O. Scully, "Optical Magnetometry in Dense Coherent Media," ONR Workshop on Quantum Optics, Jackson Hole, WY, August, 2000.
9. G. Welch and M. O. Scully, "Experiments with Slow Light," International Workshop on Laser Physics (LPHYS'2000), 16 July 2000, Bordeaux, France.
10. M. O. Scully, Applications of quantum coherence in fundamental and applied physics, invited talk on Conference on Lasers and Electro-Optics Quantum Electronics and Laser Science Conference, San Francisco, California 2000, report QFC1.
11. M. O. Scully, H. Z. Cummins, A. B. Matsko, and Y. V. Rostovtsev, Quantum noise suppression via atomic coherence effects, invited talk on at the workshop "Physics and Applications of "Slow" Light" at Harvard-Smithsonian Center for Astrophysics, Boston, 2000.
12. M. O. Scully, Coherent control meets thermodynamic dogma, invited talk on 30<sup>th</sup> Colloquium on the Physics of Quantum Electronics, Snowbird, Utah, 2000.
13. M. O. Scully, L. Hollberg, O. Kocharovskaya, M. M. Kash, V. Sautenkov, S. Zibrov, E. S. Fry, M. D. Lukin, A. B. Matsko, Y. Rostovtsev, G. R. Welch, Resonant nonlinear optics in phase coherent media, 1999 OSA Annual Meeting Santa Clara, California, report TuN3.
14. Marlan O. Scully and Kishor T. Kapale, "Does the Critical Temperature Concept Make Sense for Bose Einstein Condensation in Mesoscopic Systems? Or Is There an Easy Resolution to the Uhlenbeck Dilemma?," in *Proceedings of Richard L. Arnowitt Fest*.

15. M. O. Scully, H. Lee, E. Gomez, and R. O.-Martinez "A tutorial on quantum distribution functions for spin 1/2 systems and EPR correlations," in Proceedings of Latin American School of Physics "New perspectives on quantum mechanics" XXXI ELAF'98 ed. by S.Hacyan, R.J.-Renaud, and R.L.-Pena, (Mexico City 1998) p.221.
16. M. O. Scully, Y. Aharonov, and B. G. Englert, On the locality and reality of EPR correlations, in "Mysteries, puzzles, and paradoxes in quantum mechanics" ed. by R. Bonifacio, 47 (1999).
17. M. O. Scully, "BEC and the laser phase transition analogy" Physics of Quantum Electronics (Snowbird, Utah).

### **Honors/Awards/Prizes for contract/grant employees**

1. Invited to give the Eastman Lecture (Optical Society of America), University of Maryland, April 16, 2002
2. M. O. Scully is elected to membership in the National Academy of Sciences, 2001
3. M. O. Scully is elected to membership in the European Academy of Sciences (Europea Academia), 2001;
4. M. O. Scully received Sigma XI Outstanding Scientific Communicator Award, 2001;
5. 1999 Texas A&M University Distinguished Research Achievement Award to M. O. Scully.
6. K. Kapale received travel award from American Physical Society (APS) to present talks at the Texas Section APS meeting held at Sam Houston State University March 1-3, 2001;
7. K. Kapale received Gordon Research Conference (GRC) Poster Award with financial support, to present a poster at GRC in Atomic Physics, Williamstown, MS, June 17-22, 2001;
8. K. Kapale received Pre-Thesis Research Award from the Department of Physics, Texas A&M University for the year 2000-2001;
9. "Honorable Mention Award" of Texas Section of American Physical Society to Kishore Kapale 2000.